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(54) Dichroic liquid crystal displays

(57) In a dichroic dye guest-host liquid crystal display cell, the boundary conditions at the opposed surfaces of the liquid crystal layer are established such that molecules 65, 66 adjacent to one surface are parallel to the surfaces and molecules 65a, 66a adjacent to the other surface are perpendicular to the surfaces in either of the light transmissive or light absorptive conditions, thereby reducing light absorption at the boundaries in the (energised) light-transmissive condition. Absorption in the unenergised condition may be increased if the liquid crystal contains a chiral dopant, which tends to reduce the tilt of the molecules in the bulk of the layer relative to the surfaces.

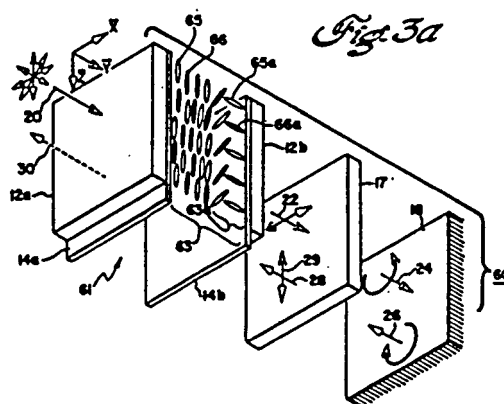


Fig. 1a
(PRIOR ART)

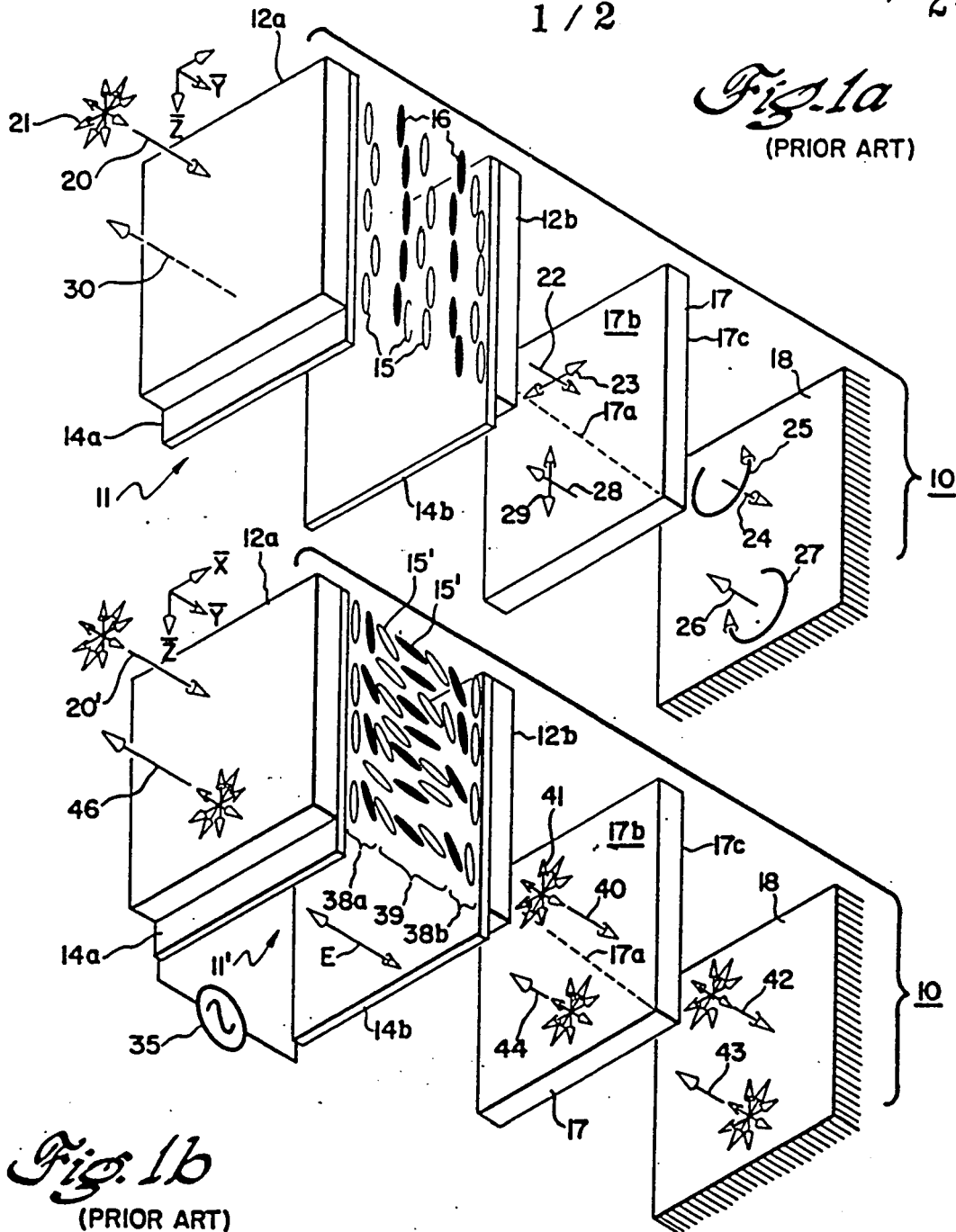


Fig. 1b
(PRIOR ART)

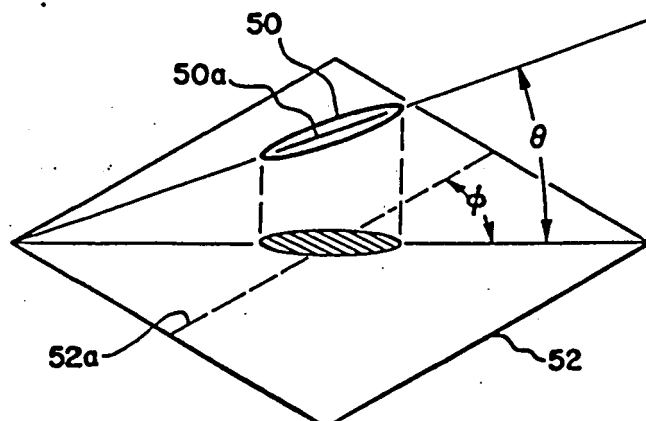
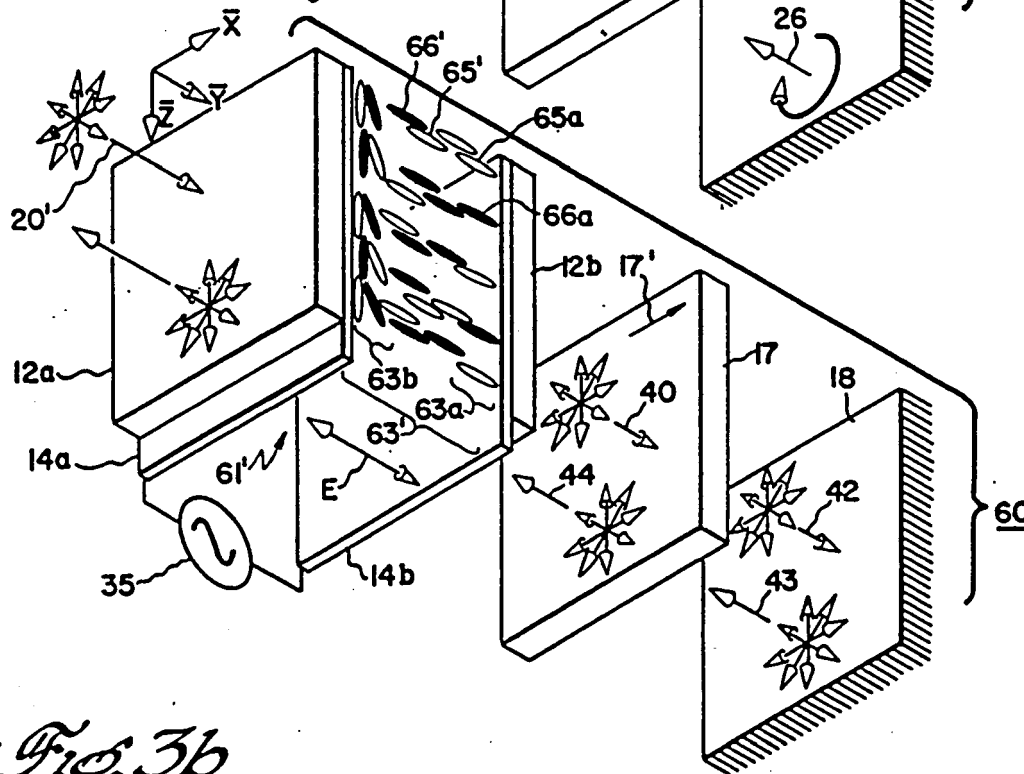
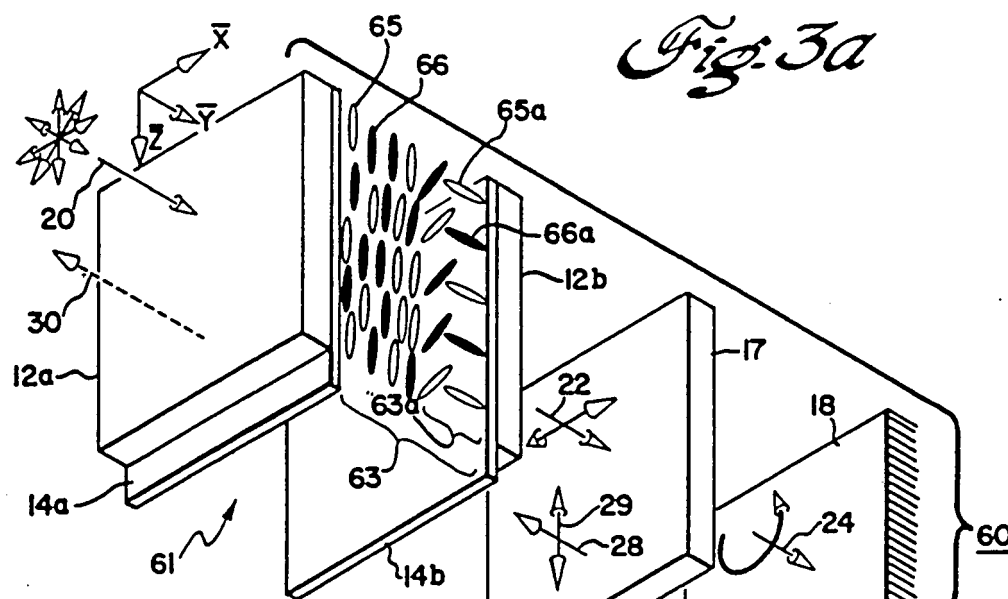


Fig. 2



SPECIFICATION

Dichroic liquid crystal displays

5 The present invention relates generally to liquid crystal displays and more particularly to a novel dichroic liquid crystal display utilizing different boundary conditions at each of the two surfaces of a dichroic liquid crystal layer, to reduce light absorption
10 in the cell in the light-transmissive condition. It is well known that liquid crystal displays may be advantageously utilized to provide low power-consumption displays. The liquid crystal display cell is a passive device, typically operated in either the
15 reflective mode, wherein ambient light is selectively reflected from portions of the display to form characters, symbols and other indicia, or in the transmissive mode, wherein light emanating from a source behind the display is transmitted through
20 selected portions of the display to form viewable indicia. The dichroic liquid crystal display, in which a guest dichroic dye is dissolved in the host liquid crystal material, has additional advantages; external elements, such as polarizers and the like, are generally
25 not required. In either mode of operation of the dichroic liquid crystal display, the brightness of the display is, however, generally limited by a number of factors, including the absorption of light at the two, opposed surfaces of the liquid crystal layer. The
30 reduction of this absorption, at the boundary layers of the liquid crystal layer, becomes especially desirable when the display cell is formed utilizing a dichroic liquid crystal layer, as the dichroic liquid crystal material is capable of providing increasing
35 contrast ratios to the cell. Accordingly, it is desirable to provide a dichroic liquid crystal display cell having decreased liquid crystal layer boundary absorption, whereby the brightness of a cell is increased.

40 In accordance with the invention, a display cell having a layer of liquid crystal material host to a guest dichroic dye, has boundary conditions at the pair of opposed layer surfaces thereof, such that the liquid crystal and dichroic dye molecules adjacent to
45 a first surface are disposed with their elongate axes parallel to that surface i.e. in the homogeneous orientation, and the liquid crystal and dichroic dye molecules adjacent to the remaining surface are disposed perpendicular to the remaining surface, i.e.
50 with the homeotropic orientation. The remaining liquid crystal and dichroic dye molecules, within the layer between the surfaces, have orientation conditions controlled responsive to the presence or absence of an electric field of suitable magnitude to
55 align these molecules either substantially parallel to the planes of the surfaces (in the non-energized, or no-field, condition) or substantially perpendicular to the planes of the surfaces (in the energized, or field-present, condition) whereby light is absorbed
60 within the bulk of the liquid crystal layer only in the non-energized (first) condition. Light absorption occurs at the parallel-disposed boundary and substantially no light absorption occurs at the perpendicularly-disposed boundary, for both the energized
65 and non-energized conditions.

In a preferred embodiment, the boundary conditions of the dichroic liquid crystal layer are established by suitable treatment of each of a pair of substantially transparent conductive electrodes
70 positioned adjacent to an associated surface of the dichroic liquid crystal layer. The electrode adjacent to the perpendicularly-disposed boundary is treated with a suitable surfactant while the electrode adjacent to the parallel-disposed boundary of the liquid
75 crystal layer, wherein the molecules have a relatively low tilt angle, is produced by means of obliquely evaporated silicon oxide layers.

Figures 1a and 1b are exploded prospective views of a prior art reflective dichroic liquid crystal display cell, illustrating the manner of operation thereof and the light absorption at the boundaries of the liquid crystal layer;

Figure 2 is a prospective view useful in defining the tilt and twist angles formed by the axes of a liquid crystal or dichroic dye molecule, with respect to a molecular layer-electrode boundary surface; and

Figures 3a and 3b are exploded prospective views of a novel dichroic liquid crystal cell, of the reflective type, utilizing the principles of the present invention.

Referring initially to *Figures 1a and 1b*, where like elements are designated with identical reference numerals, a prior art dichroic display 10 includes a liquid crystal display cell 11 having a pair of spaced
95 planar transparent substrates 12a and 12b, which may be advantageously formed of materials such as optical glass and the like, and which substrates are arranged substantially parallel each to the other. A substantially transparent electrode 14a or 14b is
100 deposited upon each facing interior surface of respective substrates 12a and 12b and may be selectively etched to define alphanumeric symbols and other indicia to be displayed by cell 10. Advantageously, electrodes 14a and 14b may be formed of
105 materials such as tin oxide (SnO_2), indium oxide (In_2O_3) and the like. A layer (not shown for purposes of simplicity) of silicon oxide (SiO) is obliquely deposited upon the interior facing surfaces of the electrodes to act as an aligning film, as taught in U.S.
110 Patent 3,834,792.

The volume between spaced electrodes 14a and 14b is filled with a layer comprising molecules 15 of a liquid crystal material acting as a host for molecules 16 of a guest dichroic dye characterized by a sufficiently high order parameter to provide a high contrast ratio. As illustrated, molecules 15 are of a liquid crystal composition having a net positive dielectric anisotropy, i.e., the dielectric constant of the material in a direction parallel to the long
120 molecule axis, or director, is greater than the dielectric constant in a direction perpendicular to the molecule direction. In the quiescent state, the directors of such a nematic liquid crystal compound tend to align all of molecules 15 both parallel to each
125 other and in a single direction, which direction is illustrated herein as being the Z axis, as facilitated by the afore-mentioned SiO aligning film. Molecules 16 of a guest dichroic dye are dissolved in the nematic liquid crystal composition in sufficient quantity to
130 achieve adequate light absorption as hereinafter

described below. Dye molecules 16 are aligned with their long axes or directors parallel to, and interspersed between, the directors of the nematic liquid crystal molecules 15. One suitable "guest-host" composition utilizes a positive dielectric anisotropy liquid crystal mixture of ester-type compounds having a mesophase including room temperature, in which mixture is dissolved a dichroic dye material, such as Sudan Black B and the like, in an amount of approximately 0.5% by weight of the liquid crystal mixture. This display cell may be operated in either the transmissive mode or, as illustrated, in the reflective mode. In the reflective mode, a plate 17 of a material exhibiting optical birefringence is arranged with its optical axis 17a aligned at a 45° angle with respect to the directors of liquid crystal molecules 15 and dichroic dye molecules 16. Thus, optical axis 17a is aligned along the vector $(\bar{X} + \bar{Z})$, where direction vector \bar{X} is orthogonal to direction vector \bar{Z} with vectors \bar{X} and \bar{Z} forming a plane coplanar with the planes of substrates 12a and 12b. Plate 17 has a pair of essentially parallel spaced exterior surfaces 17b and 17c separated each from the other by a distance sufficient to cause plate 17 to be a quarter-wave plate, i.e., to retard one of the doubly-refracted optical waves by essentially 90° with respect to the remaining one of the optical waves. Advantageously, plate 17 may be formed of a material such as quartz, calcite, mica or the like.

Reflector means 19, which may be a polished mirror or the like, is of a planar shape and is essentially completely in abutment against one exterior surface 17c of quarter-wave plate 17, whose opposite exterior surface 17b is essentially completely in abutment against the exterior surface of rear substrate 12b.

In operation, the use of the aligning film on both electrodes 14a and 14b causes liquid crystal molecules 15 and guest dichroic dye molecules 16 to be aligned substantially parallel (homogeneous) to the plane of substrates 12a and 12b, when a field is not present between the electrodes (Figure 1a). A beam 20 of ambient light, which is unpolarized as indicated by the plurality of polarization vectors 21, is directed along the \bar{Y} axis to impinge upon and be transmitted through transparent front substrate 12a and semi-transparent front electrode 14a. Incident polarized light 20 is preferentially absorbed by the parallel aligned dichroic dye molecules 16 where a light beam 22 exiting in the \bar{Y} direction through rear electrode 14b and rear substrate 12b is transmitted with linear polarization in the \bar{X} direction (orthogonal to the elongated axes of dye molecules 16, aligned in the \bar{Z} direction). The polarization of exiting beam 22 is indicated by polarization vector 23. The linearly- \bar{X} polarized light beam 22 passes through quarter-wave plate 17 and is converted to a beam 24 of circularly polarized light having, as illustrated, a left-handed (counterclockwise) polarization vector 25. Circularly polarized light beam 24 impinges upon and is reflected by reflector means 18, which reflection causes the sense of circularly polarized beam 26 to be reversed to a right-handed (clockwise) polarization vector 27. The reverse-circularly polarized light beam 26 is transmitted through quarter-wave plate

17 in a direction opposite to the transmittal direction along the \bar{Y} axis of light beam 22 and hence exits from exterior surface 17b of plate 17 as a light beam 28 which is linearly polarized in the \bar{Z} direction, as indicated by polarization vector 29. Polarization vector 29 is aligned parallel to the directors of dichroic dye molecules 16 and, as the director-parallel direction is the high-absorption direction for the dichroic dye molecules utilized, substantially all of the optical radiation in beam 28 is absorbed by molecules 16, whereby the intensity of optical beam 30, shown in dashed line, reflected from display 10 is of very low (substantially zero) magnitude; the incident optical energy in beam 20 being lost partially through scattering and absorption during passage through the various elements of the display but primarily being absorbed by dye molecules 16.

A voltage source 35 (Figure 1b) is connected between spaced electrodes 14a and 14b to generate an electric field E in the \bar{Y} direction, causing liquid crystal molecules 15' to be essentially realigned with their directors lying predominantly in the \bar{Y} direction. It is important to note that a thin "layer" 38a and 38b of molecules 15 and 16 closest to each of substrates 14a and 14b, remain substantially in their quiescent alignment positions and parallel to the planes of the liquid crystal layer and of the electrodes 14a and 14b, even when the field is applied. In the central portion 39 of the layer, the guest dichroic dye molecules 16', being dissolved in the host liquid crystal material, are realigned along with the liquid crystal molecules to have directors lying substantially in the \bar{Y} direction. In this active, or "on", condition, beam 20' of incident unpolarized light is affected by the orientation of dichroic dye molecules 16' only in the thin "layers" 38a and 38b in which the molecular axes are still parallel to the layer surfaces, wherein preferential absorption still occurs. The beam 40 of optical energy exiting from the exterior surface of rear substrate 12b is substantially randomly polarized, as shown by polarization vectors 41, and is transmitted by quarter-wave plate 17 with substantially no effect to emerge as optical beam 42 of unpolarized light, which beam 42 is reflected by reflector means 18 as a beam 43. Beam 43 is re-transmitted through quarter-wave plate 17 as another beam 44 of light, which again passes substantially through the \bar{Y} aligned molecules of display cell 11' and undergoes additional attenuation by absorption in the pair of thin "layers" 38a and 38b, prior to the beam emerging as a reflected beam 46 of optical energy. The brightness of reflected beam 46 is somewhat less than that of incident beam 20' due to passage through a total of four absorbing "layers" (i.e. layers 38a and 38b in the + \bar{Y} direction and layers 38b and 38a in the - \bar{Y} direction); the brightness of "reflected" beam 30, in the "off", or inactive condition of the cell, is minimal in comparison to incident beam 20. The ratio of the "on" condition reflected beam 42 to the "off" condition beam 30 is the contrast ratio defined for a display cell 10; this contrast ratio is directly related to the order parameter of the dichroic dye used therein, especially as scattering and transmission-attenuation losses may be minimized by selection of

sufficiently high quality optical materials for substrates 12a and 12b, quarter-wave plate 17 and reflector plate 18. The higher the order parameter, the greater will be both the attenuation resulting in the quiescent state and the contrast ratio. However, the total brightness, and to some extent the contrast ratio, is determined by the amount of absorption in "layers" 38a and 38b.

Referring now to Figure 2, a liquid crystal or dichroic dye molecule 50, having an elongated axis 50a, may be disposed with its elongated axis at some tilt angle θ with respect to the surface of a plane 52 and may also be disposed at a twist angle ϕ with respect to a line 52a upon that surface. Thus, in the prior art display described hereinabove, the liquid crystal and dichroic dye molecules disposed in the thin "layers" 38a and 38b (adjacent to the surfaces of the liquid crystal layers and the planar surfaces of the adjacent electrodes) are disposed with a tilt angle substantially equal to 0° , as the elongated molecular axes in these regions lie substantially parallel to the boundaries between the liquid crystal layer and the adjacent electrodes. It will also be seen that the twist angle ϕ is very low, and may even approach zero for dichroic liquid crystal compositions of high order parameter, in these layers. Similarly, it is seen that the energized liquid crystal layer of Figure 1b has liquid crystal and dye molecules in the central region 39 thereof having tilt angles progressively increasing from about 0° to a maximum of about 90° and then decreasing toward a final tilt angle, at the opposite boundary, of about 0° .

Referring now to Figures 3a and 3b, in a preferred embodiment of my novel dichroic liquid crystal display 30, as utilized in the reflective mode, and wherein like elements, with respect to Figures 1a and 1b, are described by like reference designations, a display cell 61 is sequentially followed by a quarter wave plate 17 and reflector 18. Display cell 61 includes front and rear substrates 12a and 12b having substantially transparent conductive electrodes 14a and 14b upon the facing interior surfaces thereof. A layer 63 of dichroic liquid crystal material is enclosed in the volume between the parallel planar electrodes. One of electrodes 14a and 14b is treated, as by obliquely evaporating a layer of silicon oxide (SiO) thereon, to cause the liquid crystal molecules 65 and guest dichroic molecules 66 adjacent to the boundary defined by that electrode, to align parallel to the electrode surface. In the illustrated embodiment, the parallel alignment (homogeneous) condition is produced at the boundary defined by the inner surface of electrode 14a. The tilt angle of the molecules adjacent to the surface of electrode 14a is thus relatively small and is generally less than 30° , with tilt angles ideally approaching 0° .

The inner surface of remaining electrode 14b is treated, as with a surfactant or a silane coupling agent, to provide a homeotropic boundary condition, wherein the liquid crystal molecules 65a and dichroic dye molecule 66a adjacent to this boundary are aligned with their elongated axes substantially perpendicular to the electrode plane. Thus, the majority of liquid crystal and dichroic dye molecules between the spaced apart electrodes, are in the

homogeneous (parallel) orientation, with only a relatively small proportion of the molecules, adjacent electrode 14b, having tilt angles approaching 90° .

In operation, the use of the different surface treatments on electrodes 14a and 14b causes the liquid crystal and dichroic dye molecules adjacent to the electrode having the obliquely evaporated silicon oxide layer to always remain in the homogeneous condition, while the liquid crystal and dichroic dye molecules adjacent to the other electrode, having the surfactant or silane coupling agent treatment, always remain substantially in the homeotropic boundary condition. A beam of light 70 (Figure 3a) directed along the \bar{Y} axis, impinged upon the substantially transparent front substrate 12a and is transmitted therethrough substantially without attenuation. The unpolarized beam 20 is then transmitted through front electrode 14a and encounters the parallel-aligned dichroic dye molecules 66 adjacent to front electrode 14a and the majority of the thickness of the dichroic liquid crystal layer 63, whereby preferential absorption of light polarized in the \bar{Z} direction occurs. The light is thus linearly polarized prior to passage through homeotropic layer portion 63a, wherein relatively little absorption occurs due to the orthogonality of the directors and the polarization vectors. The linearly \bar{X} polarized light beam 22 passes through quarter-wave plate 17 for conversion to a beam 24 of circularly polarized light having the illustrated left-handed polarization vector 25. The circularly polarized light beam 24 is reflected by reflector means 18 to cause a reverse-circularly polarized light beam 26 to be transmitted in the \bar{Y} direction through the quarter wave plate and to emerge therefrom as a light beam 28 which is linearly polarized in the \bar{Z} direction, as indicated by polarization vector 29. Beam 28 again passes through rear substrate 12b and rear electrode 14b in substantially unattenuated manner, and initially encounters the homeotropic liquid layer portion 63a, wherein relatively little absorption occurs. The beam then passes through the remaining portion of the liquid crystal layer, which remaining portion is in the homogeneous orientation, with dichroic dye molecule directors parallel to the polarization vector 29 of the beam, whereby the remainder of the light energy is absorbed and a "beam" 30, of substantially zero magnitude, emerges from the display. Thus, in the "off", or unenergized, condition, display 60 is viewable as a relatively dark display, in which all of the entering light is absorbed, even though one liquid crystal layer boundary condition is of the homeotropic type.

In Figure 3b, voltage source 35 is connected between space for electrodes 14a and 14b to generate the electric field E in the Y direction to cause the liquid crystal molecules 65' and the dichroic dye molecules 66' in the central bulk of liquid crystal layer 63', to assume the homeotropic orientation parallel to molecule 65a and 66a of layer portion 63a. A thin "layer" 63b of the dichroic liquid crystal material adjacent to front electrode 14a remains in the homogeneous condition, with molecular directors parallel to the electrode surface, due to the

action of the homogeneous-boundary surface condition thereat. Thus, the molecules adjacent to the surface of front electrode 14b have relatively low tilt angles, ideally approaching zero degrees, with the tilt angles for molecules sequentially positioned towards the rear electrode 14b sequentially and rapidly increasing toward a tilt angle of 90° in the bulk and portion 63a adjacent the rear electrode.

The randomly-polarized entering light beam 25 passes substantially unattenuated through front substrate 12a and front electrode 14a, and is then transmitted through the homogeneous portion 63b of the liquid crystal layer, where some small amount of absorption occurs. The partially-absorbed beam is transmitted through the remainder of the liquid crystal layer 63' with substantially no additional absorption, as the remainder of the molecules are in the homeotropic condition. Thus, beam 40 of substantially randomly polarized light exits from cell 61', is transmitted by quarter-wave plate 17 with substantially no effect on the polarization thereof, emerges from the quarter-wave plate as a beam 42 of unpolarized light that is reflected by reflector means 18 as a beam 43 of unpolarized light and is again transmitted through the quarter-wave plate to emerge therefrom as a substantially unpolarized beam 44 of light directed toward the rear substrate 12b of cell 61 prime. Beam 44 passes sequentially through layer portions 63a and the bulk of layer 63' in substantially unattenuated manner, due to the homeotropic orientation of the dichroic dye molecules 66a and 66' thereof. Passage through layer portion 63b causes some additional attenuation due to the homogeneous orientation of the dichroic dye molecules thereof, orthogonal to the direction of light travel and parallel to the front electrode planar surface. Upon passage through front electrode 14a and front substrate 12a, beam 46 emerges with substantially random polarization and a brightness somewhat diminished over the brightness of entering beam 20', due to the two passages through the homogeneous layer portions 63b. It will be seen that this attenuation is only one-half of the attenuation due to the pair of passages through the pair of "layers" 38a and 38b in the prior art cell of Figure 1b, wherein the homogeneous orientation is utilized at both crystal layer boundaries. Thus, a brighter display is apparent with the use of only a single homogeneous boundary condition (the other boundary condition being a homeotropic boundary) while the apparent contrast appears to increase.

Having improved the brightness of the cell in the "on" or energized condition, the apparent contrast may be further improved by increasing the absorption of the cell in the "off", or on-energized, condition, by the addition of a small amount of chiral dopant to liquid crystal layer 63. The addition of a small amount of chiral dopant tends to reduce the average tilt angle θ of the molecules within the bulk of layer 63, in the "off" state, due to the chiral nematic liquid crystal composition having a preferred state with a helical structure, with zero tilt, in a plane parallel to the plane of the electrodes. The amount of chiral dopant is selected to lie between two limiting conditions: the pitch of the resulting

chiral nematic dichroic liquid crystal material should be relatively long with the wavelength of light in the liquid crystal material, whereby light will propagate with as near to linear polarization as possible; and the pitch must be sufficiently long, i.e. the pitch greater than or approximately equal to the layer thickness, such that a uniform single crystal layer may be formed. The result of using a chiral nematic dichroic liquid crystal material in a display cell having one homogeneous and one homeotropic boundary to produce high "off" absorption and reduce "on" absorption, respectively, may result in an improved contrast ratio by as much as the square of the contrast ratio previously obtainable with a display cell of the type shown in Figures 1a and 1b. It should be understood that, while a reflective mode dichroic liquid crystal display has been utilized herein for purposes of illustration, a dichroic liquid crystal display operating in the transmissive mode may be provided, using the principle of opposed boundary conditions for the liquid crystal layer, to provide the same advantages. A transmissive mode display may be fabricated by replacing quarter-wave plate 17 with a linear polarizing element having its polarization vector 17' (Figure 3b) disposed orthogonal to the directors of the dichroic dye molecules in the homogeneous "layer" 63b adjacent to one of the electrodes; reflector means 18 would then be replaced by a rear-positioned light source.

CLAIMS

1. A liquid crystal display cell comprising; a layer of dichroic liquid crystal material having opposed first and second surfaces; a first means for aligning the liquid crystal molecules at the first surface such that the molecules assume a homogeneous orientation; second means for aligning the liquid crystal molecules at the second surface such that the molecules assume a homeotropic orientation; and third means for switching the molecules in the remainder of the layer between a homogeneous and a homeotropic orientation.
2. A display cell of Claim 1, wherein the layer is sandwiched between first and second substantially transparent electrodes.
3. The display cell of Claim 2, wherein said first means is a film obliquely deposited upon that surface of the first electrode in contact with the first surface of the layer.
4. The display cell of Claim 3, wherein the film is of silicon oxide.
5. The display cell of Claim 2, wherein said second means is one of a surfactant and a silane coupling agent deposited upon that surface of the second electrode in contact with the second surface of the layer.
6. The display cell of Claim 2 wherein the third means includes a source of electrical potential for connection between said first and second electrodes to provide an electric field through said dichroic liquid crystal layer of sufficient magnitude to change the orientation of the molecules in the remainder of the dichroic liquid crystal layer.
7. The display cell of Claim 2, further comprising

first and second substantially transparent substrates respectively supporting the respective first and second electrodes.

8. The display cell of Claim 7, further including
5 optical means acting in conjunction with said cell for forming a display operating in at least one of the reflective and transmissive modes.

9. The display cell of Claim 1, wherein said display includes means for reducing the average tilt
10 angle of the dichroic liquid crystal molecules in the homogeneous condition.

10. The display of Claim 9, wherein the tilt angle reducing means is a quantity of a chiral dopant dissolved in the dichroic liquid crystal material.

15 11. A display cell according to Claim 1 and substantially as herein described with reference to Figure 3 of the accompanying drawings.

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